

Flight Deck-Based Delegated Separation: Evaluation of an On-board Interval Management System with Synthetic and Enhanced Vision Technology

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An emerging Next Generation Air Transportation System concept - Equivalent Visual Operations (EVO) - can be achieved using an electronic means to provide sufficient visibility of the external world and other required flight references on flight deck displays that enable the safety, operational tempos, and visual flight rules (VFR)-like procedures for all weather conditions. Synthetic and enhanced flight vision system technologies are critical enabling technologies to EVO. Current research evaluated concepts for flight deck-based interval management (FIM) operations, integrated with Synthetic Vision and Enhanced Vision flight-deck displays and technologies. One concept involves delegated flight deck-based separation, in which the flight crews were paired with another aircraft and responsible for spacing and maintaining separation from the paired aircraft, termed, “equivalent visual separation.” The operation required the flight crews to acquire and maintain an “equivalent visual contact” as well as to conduct manual landings in low-visibility conditions. The paper describes results that evaluated the concept of EVO delegated separation, including an off-nominal scenario in which the lead aircraft was not able to conform to the assigned spacing resulting in a loss of separation.

Introduction

The U.S. air transportation system is undergoing a transformation to accommodate the movement of large numbers of people and goods in a safe, efficient, and reliable manner. One of the key capabilities envisioned to achieve this Next Generation Air Transportation System (NextGen) is the concept of Equivalent Visual Operations (EVO).

Equivalent Visual Operations

The operational concept, EVO, strives to replicate the airport capacity and safety now achieved under Visual Flight Rules (VFR) in all weather conditions.

NASA is investigating the potential of flight deck technologies to create an EVO capability by providing an electronic means of ‘visibility’ for the flight crew. Synthetic/Enhanced Vision System (S/EVS) technologies are envisioned as one of the critical enabling technologies to EVO. The capabilities of these technologies has been recognized and an important precedent have been set under recent changes to the US Federal Aviation Regulations - an approved Enhanced Flight Vision System may now be used in lieu of a pilot’s natural vision to conduct an instrument approach [1].

VFR operations historically provide better airport throughput and capacity than Instrument Flight Rules (IFR) operations; however, VFR, and by analogy, EVO is far from ideal. The concept of “Better Than Visual” [1] - replicating the capacity of today’s VFR flight and more importantly, meeting *and improving* on the safety of today’s VFR flight in all-weather NextGen operations – is being pursued by NASA. This capability builds from today’s VFR operations and adds elements of stabilized approach procedures, predictable operations, and structured protocols, among others, which historically have improved safety (see for example, [2]). The BTV operational concept also leverages on procedural and technological innovations that are being developed to support NextGen operations, such as Flight Deck Interval Management (FIM).

Flight Deck Interval Management

The Federal Aviation Administration's Surveillance and Broadcast Services Program Office considers Flight Deck Interval Management (FIM) to be one of the three key, near-term applications to make use of Automatic Dependent Surveillance – Broadcast (ADS-B)-In - the receiving and processing of ADS-B data on-board an aircraft.

The FIM applications are sub-divided into two categories: one where the flight crew is authorized to manage their speed to achieve the FIM goal, while the controller retains separation responsibility; and a second where the flight crew takes responsibility for both management of their speed and separation from the specified paired aircraft. The former is referred to as Flight Deck Interval Management-Spacing (FIM-S) and the latter as Flight Deck Interval Management-Delegated Separation (FIM-DS).

Flight Deck Interval Management – Spacing (FIM-S). Merging multiple aircraft into a manageable sequence and control of their spacing during arrival and approach, while managing aircraft energy in an environmentally friendly way, is crucial to increasing productivity of the National Airspace System (NAS). The concept of FIM seeks to enhance airport efficiency through the scheduling and management of aircraft-to-aircraft spacing at the runway threshold through precision spacing and on-board speed guidance. Using FIM, the Air Navigation Services Provider (ANSP) instructs the participating aircraft to achieve an assigned inter-arrival spacing interval at the runway threshold, relative to another aircraft, using on-board automation. The flight crew takes responsibility to achieve the FIM operation spacing objective but the ANSP retains the responsibility for aircraft separation operating under Instrument Flight Rules (IFR).

Today, airport arrival rates are directly affected by surveillance accuracy and latency and minimum separation requirements have been established based on these factors as well as the influence of runway configurations, runway occupancy times, and wake turbulence separation criteria. FIM-S does not change separation criteria per se. The benefits of FIM-S are derived primarily by improved precision in delivering and spacing aircraft. NASA research has demonstrated the

efficacy of the concept and the stability and value of system-wide effects and algorithm performance to significantly increase arrival throughput rates of up to 20% compared to traditional positive air traffic control (e.g., [3] – [12]).

Flight Deck Interval Management - Delegated Separation (FIM-DS). FIM-DS extends the FIM-S concept by changing responsibility for separation from the ANSP to the FIM aircraft flight crew. It is important to note that today a visual clearance is *delegated* separation (see [13]); therefore, FIM-DS is an extension of VFR delegated separation, during FIM operations.

FIM-DS is expected to bring even greater benefits than FIM-S. Since the controller will delegate separation responsibility to the flight crew, controller workload is expected to be reduced (e.g., [14]). Note that FIM-DS does not delegate full separation responsibility as in a self-separation application. The FIM aircraft is only responsible for separation from the ATC-specified paired aircraft for the duration of the FIM-DS operation; the ANSP remains responsible for separation between the FIM Aircraft and all non-Paired (i.e., not paired with ownship) Aircraft.

Since separation responsibility from the paired aircraft will be delegated to the FIM aircraft, the FIM aircraft may be cleared to space closer to the separation standards than during similar FIM-S operations. During a FIM-S operation, the assigned spacing goal must include time for the ANSP, using latent and imprecise surveillance data, to detect and intervene before separation is lost. During FIM-DS operations, that additional time between the assigned spacing goal and separation standard may be reduced or eliminated with pilot responsibility for separation.

The FIM-DS concept offers many potential operational benefits (see Figure 1) but also raises many questions.

Significant safety concerns are directly associated with how the conflict detection/separation assurance function can be performed by the flight crew. Acceptance, compliance, and workload for pilot responsibility of separation are major concerns.

One concept for FIM-DS relies on the use of Cockpit Display of Traffic Information (CDTI) to enable the delegated separation [e.g., 13]. The primary limitation of this concept is that the FIM-enabling technology – ADS-B In – is also being relied upon for separation assurance. The use of a

single source of information with its inherent frailties may create unacceptable failure mode effects.

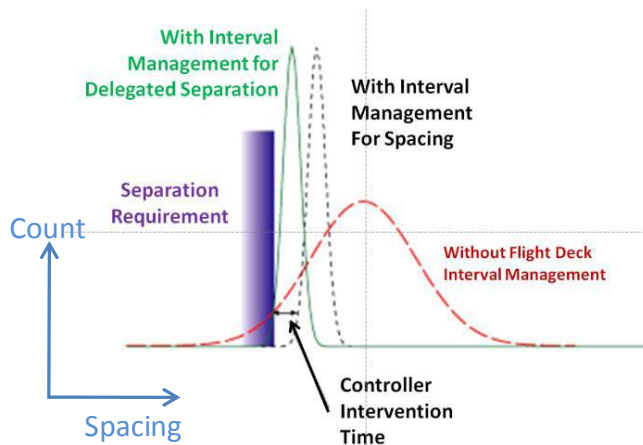


Figure 1. Flight-Deck Interval Management Benefits

In contrast, the concept explored in this experiment combines the use of FIM-S equipment with a system and/or procedures that allow for visual-like, or equivalent visual separation. The use of Enhanced Flight Vision Systems (EFVS) – embracing the precedence that EFVS may be used in lieu of natural vision – may enable FIM-DS using redundant, dissimilar information. The flight crew would monitor their separation from the paired aircraft using the S/EVS technology under the assumption that EFVS provides visual acquisition and separation from the paired aircraft. The flight crew continues to achieve or maintain their assigned FIM spacing goal while also maintaining visual-like separation.

Experiment Objectives

The primary objective of the research compared the efficacy, acceptability, and flight deck-centric effects of FIM-S and FIM-DS. Currently, approaches to FIM are concentrated on spacing-only applications or enhancing VFR operations (e.g., CDTI-assisted visual separation; enhanced visual approaches). There exists little research on delegated separation although pilot acceptance of the operational concept has been established [15]; a notable exception being the distributed air-ground

traffic management autonomous flight rules research for en-route flight (e.g., [16] – [19]). The experiment evaluated the flight deck aspects of integrating FIM and S/EVS technologies to support NextGen.

Methodology

Pilot Participants

Twenty-four pilots participated, serving as twelve flight crews. Ten crews, who flew for major U.S. air carriers, were paired by airline to ensure crew coordination and cohesion with regard to standard operating procedures. The other crews were business aircraft operators, flying Gulfstream G-V or G450 aircraft equipped with EFVS and SVS. The Captains were recruited on the basis of HUD experience (at least 100 hours), with preference given to pilots with EFVS experience.

Experimental Design

The experiment design was a two-level factor mixed-subjects study. It was conducted over two days of testing and this work was the first (i.e., conducted on Day 1) of two complimentary research studies.

The independent variable of interest was FIM condition: FIM-S and FIM-DS. Flight crews conducted twelve nominal runs to a simulated NextGen Chicago O'Hare Airport. Initial starting position was varied and runs were randomly assigned across the twelve flight crews. All flight crews flew six approaches with each FIM condition yielding twelve total nominal runs. The last trial (Trial #13) was an off-nominal condition that was between-subjects in which the FIM condition was randomly assigned providing six data trials for each of the two FIM conditions across all pilot participants. The design masked the off-nominal trial and created an unexpected FIM event. The flight crews were not aware of the number of trials being conducted and were not instructed that the final trial was the last to be conducted on that day of testing; the flight crews reported that they were entirely unaware that an off-nominal condition would be presented to them although they were instructed on a number of potential scenarios that could arise with FIM generally and to be vigilant to

potential problems as expected during any flight operation. The nominal and off-nominal trials are described below.

Flight Deck Full-Mission Simulation

The research was conducted in the Research Flight Deck (RFD) simulator at NASA Langley Research Center (Figure 2). The full-mission RFD simulates a large commercial jet transport aircraft.

The RFD is configured with four 10.5-inch Vertical (V) by 13.25-inch Horizontal (H), 1280x1024 pixel resolution color displays, tiled across the instrument panel. Also, the RFD includes a HUD on the left side of the cab, Mode Control Panel, Flight Management System (FMS), and two Electronic Flight Bags (EFBs).

The full-mission RFD simulates a Boeing B-757-200 aircraft, albeit controlled through sidestick levers. A collimated out-the-window scene is produced by an Evans and Sutherland Image Generator graphics system providing approximately 200° H by 40° V field-of-view at 26 pixels per degree.



Figure 2. NASA Full-Mission Flight Simulator

Figure 3 (below) shows the simulator's four main instrument panel displays used in the trials described here: a) Pilot Flying (PF) left display, including primary flight display (PFD); b) PF right display including navigation display (ND); c) Pilot Not Flying (PNF) left display, including ND; and, d) PNF right display, including PFD.

Automatic Dependent Surveillance Broadcast (ADS-B)

Automatic Dependent Surveillance Broadcast (ADS-B) performance and message sets were modeled on the basis of RTCA DO-242A. The ADS-B data was received and sent through a simulated ARINC 429 data bus channel with an update rate of 1 Hz. Expected ADS-B In inaccuracies were simulated. Airborne traffic position (p) and velocity (v) data included Gaussian position and velocity errors about their true values representative of RTCA DO-289, Navigation Accuracy Category (NACp) = 9 (i.e., 95% accuracy bound on horizontal position of 30 m) and NACv = 2 values (i.e., 95% accuracy bound on horizontal velocity of 3 m/sec). Surface traffic (i.e., aircraft with altitudes less than 100 ft height above threshold elevation) included Gaussian position and velocity errors about their true values representative of NACp = 11 values (i.e., 95% accuracy bound on horizontal position of 3 m) and NACv = 4 values (i.e., 95% accuracy bound on horizontal velocity of 0.3 m/sec). Between updates, the traffic position data was estimated by first-order inter-sample projection of the 1 Hz data. An ADS-B latency of 0.6 seconds was also emulated. Although FIM-S applications may only require a minimum NACp of 7 (185.2 m) and NACv of 2 (< 3 m/sec), the higher NACp values were used instead loosely following DO-289 expectations and the possibly more stringent requirements for FIM-DS.

Head-Up Display

The RFD is equipped with a Rockwell-Collins HGS-4000 HUD. The HUD is collimated and subtends approximately 26° H by 21° V FOV. The HUD projects the imagery from a Cathode Ray Tube source in a stroke-and-raster format. The raster input to the HUD was a simulated Forward Looking InfraRed (FLIR) source in an RS-343 format. The stroke symbology format was a modified version of the HGS Primary Mode format. The PF had independent controls to adjust the stroke symbology brightness and the raster imagery brightness and contrast and to de-clutter raster imagery and/or stroke symbology as needed.

The HUD was augmented with a "Paired Aircraft" (Target Aircraft) locator box. The locator

box was drawn at the estimated azimuth and elevation angles, computed from the Paired Aircraft ADS-B traffic information. The locator box aids in

traffic identification and correlation between the head-down CDTI and the Head-Up traffic information.

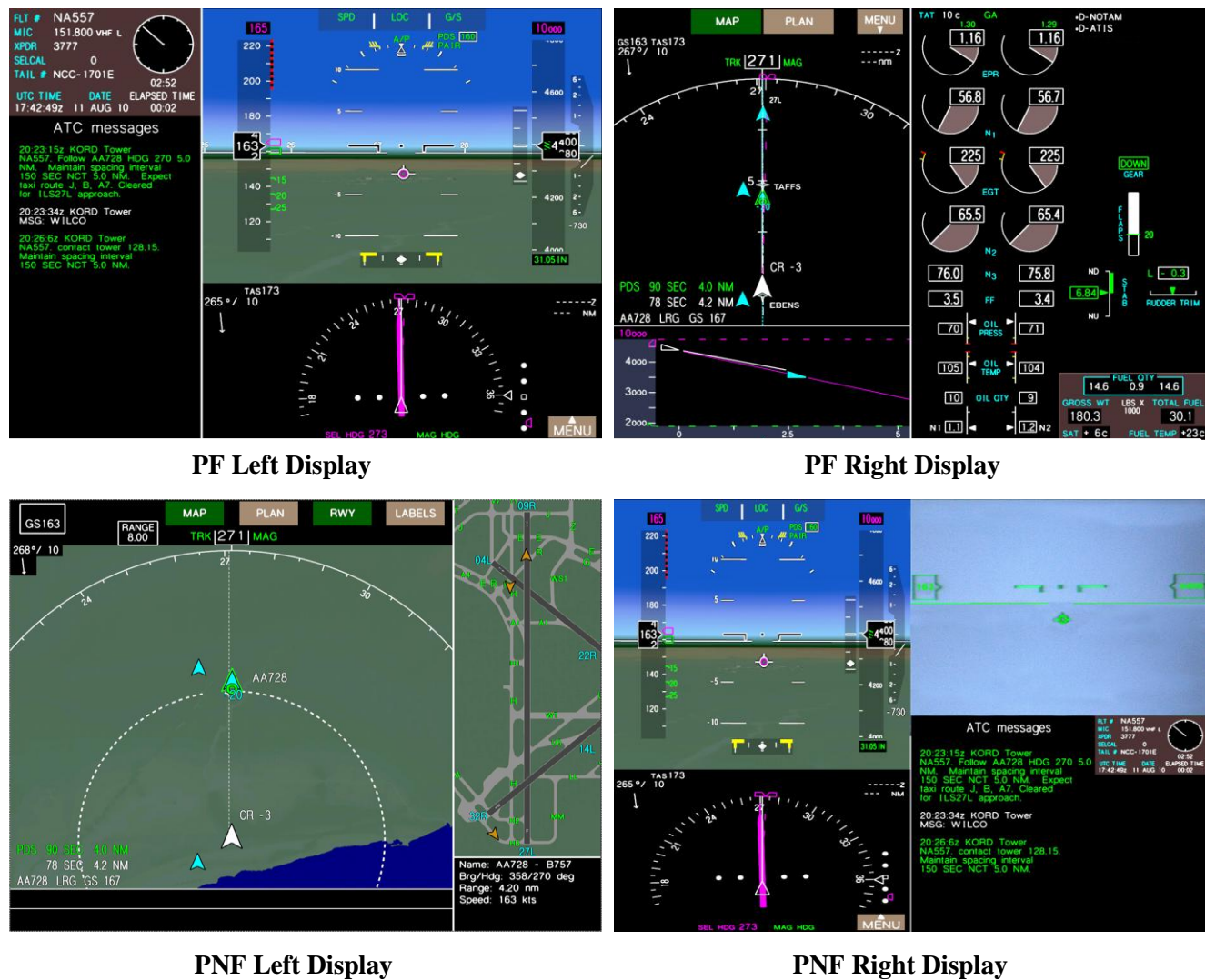


Figure 3. NASA Full-Mission Flight Simulator Main Instrument Panel Displays



Primary Flight Display

Surface Map Display

Head-Up Display

Figure 4. Surface Mode Displays

Simulator Database

Operations were simulated at Chicago O'Hare International Airport (ICAO identifier: KORD). Approaches were flown to Runways 27L and 27R during data collection. The runway lighting was displayed using calligraphics and emulated a High Intensity Approach Lighting System with Sequenced Flashing Lights. All runways included serviceable centerline, lights, and airport surface markings.

Enhanced Vision Simulation

The EV real-time simulation was created by the Evans and Sutherland physics-based sensor simulation. The KORD database was instantiated with material code properties. From this database, an IR sensor simulation, interacting with this material-coded database and the simulated weather conditions, created the desired test experimental conditions. The EV simulation mimicked the performance of a short-wave/mid-wave FLIR, using a ~1.0 to 5.0 micron wavelength detector. The nominal enhanced visibility was approximately 2400ft. for this experiment. The eye point reference for the EV simulation was placed 5 ft below the pilot design eye reference point, but otherwise properly bore-sighted (i.e., angular alignment) to the aircraft. In the simulation, the pilot is approximately 20 ft above the ground during surface operations.

Head-Down Displays

Synthetic Vision was portrayed on the PFDs using a 33° V x 44° H field-of-regard. The PFDs also had a data-link message area and Horizontal Situation Indicator. The PNF PFD used a quad-view of the same information as the PF PFD plus a FLIR repeater (upper right) with minimized symbology overlay.

The PF and PNF NDs always showed flight traffic and navigational information in the airborne mode (Figure 4) albeit with some subtle differences. The PF ND showed a standard moving map with traffic information plus an Engine Indication, Caution and Alerting System (EICAS). The PNF ND also used a moving map display with CDTI with a terrain depiction underlay.

In addition to the moving map display, the PNF ND included a runway inset view in both airborne and surface map modes. The runway inset shows a god's eye view of the selected landing runway using a landing runway-up format. All traffic information within the proximity of the landing runway was shown on this display. The displayed traffic icons on all CDTIs used the simulated ADS-B traffic information.

The PF and PNF NDs automatically transitioned to a moving map mode (0.5 nmi range) when on the ground and groundspeed was less than 80 knots; this reflects current thinking in special WG 1 of SC-186 (Figure 3).

Flight Deck Interval Management Symbolology

The head-down and head-up displays presented a number of symbolologies designed to facilitate flight crew monitoring and conformance adherence to the FIM time-based clearances and, as appropriate delegated separation, using guidance from SAE ARP5628, Appendix G (RTCA, 2003), and past NASA research on FIM-S (e.g., [4]). This information included, but was not limited to: a) Paired aircraft was denoted by an outlined chevron on the CDTI; b) commanded airspeed by the FIM algorithm was shown on the PFD; c) alphanumeric closure rate on paired aircraft was shown on the ND; and d) commanded and estimated spacing interval (measured at the runway threshold) was displayed on the ND.

Flight crews were briefed that to accept any FIM-DS clearance, the PF (on the HUD) and PNF (on the repeater display) had to observe both an ADS-B paired aircraft box and a FLIR return within that box. A progress page and a dedicated FIM page were created on the FMS CDU that enabled the flight crews to input the parameters specific to the ATC clearance to achieve the time-based objectives: either FIM-S or FIM-DS. Flight crews were briefed that the PNF should display the FIM page (Figure 5) throughout the approach and the PF should display the progress page or other pages as determined by their company standard operating procedures.



Figure 5. Approach Spacing FMS CDU Page

Flight Deck Interval Management Algorithm

The FIM-S system on the ownship used both its route and the paired aircraft's route, its planned

final approach speed, and expected runway threshold crossing time to compute speed commands for FIM. Speed commands were limited to $\pm 10\%$ of the aircraft's planned waypoint crossing speeds. This design feature helps to ensure system-wide stability and stabilized FIM operations.

The speed command control law does not require that the two aircraft are on the same route. The nominal spacing time is computed by adding the leading (paired) aircraft's calculated Time-To-Go (TTG) to the runway, based on its current position on the trajectory, to the spacing interval. The difference between this nominal spacing time and the calculated TTG to the runway for the ownship is the spacing error. More details on the FIM system and algorithm can be found in [5].

Evaluation Task

The evaluation tasks and operational procedures followed existing FIM-S protocols. The evaluation tasks involved approach and landing under 700 ft. visibility conditions involving either: (a) standard straight-in approach or (b) terminal arrival area (TAA) area navigation (RNAV) type approach that required a complex merge behind the assigned / paired aircraft already sequenced in a straight-in approach traffic stream.

During the FIM-DS trials, the flight crews were provided a FIM-S type clearance (e.g., aircraft to follow, spacing to achieve at threshold) at the onset of the trial but had the additional task of establishing an "equivalent visual contact." The flight crew had to report the Paired aircraft in view in the EFVS on the HUD; this was typically reported outside the initial approach fix. Upon reporting "visual" of aircraft and identification, the controller issued the "equivalent visual approach" clearance.

The FIM-S spacing was 150 seconds and FIM-DS was 90 seconds. These choices were based on subject matter expert opinions from pilots and KORD ANSPs (KORD Traffic Management Unit Coordinator, personal communication, July 15, 2009).

The 150 second spacing for FIM-S yielded approximately a 5.5 nmi separation crossing the threshold and the 90 second spacing provided about 3.5 nmi in-trail spacing at the threshold.

The FIM-DS condition is meant to mimic an "equivalent visual" standard (i.e., the same

separation achieved during visual conditions) and the associated benefits (i.e., lower separation standards; e.g., [20] – [22]). The assigned 90 second interval was assumed to be sufficient for wake separation.

By experiment design, the FIM-DS tested a “worse case” comparison to FIM-S for the off-nominal condition (i.e., spacing interval and distances would be significantly smaller, allowing less time for the flight crew to detect the off-nominal event). The ATC clearance included a No Closer Than (NCT) restriction of 3 nmi, which reflects the current thinking of the RTCA SC-186 and EuroCAE WG 51 committees regarding the use of NCT in a delegated separation clearance.

Off-Nominal Trial. An identical off-nominal scenario was presented to flight crews assigned to either the FIM-S or FIM-DS conditions. The scenario began and reflected the exact conditions as previous nominal trials. However, as the task continued, the lead aircraft gradually slowed down and failed to maintain the speed necessary to achieve its TTG and thus, compromised the inter-aircraft spacing. As a consequence, the ownship being flown by the flight crew participants began to receive a higher than normal number of commands to reduce airspeed. At approximately the half-way point, the FIM system no longer could issue further speed commands because of the design limitations of the algorithm which limited speed command to +/- 10% of the planned trajectory-based profile.

Once the FIM system had exceeded the +/- 10% profile speed tolerance, a caution alert was displayed on the EICAS, an aural alert sounded, and the master caution and warning light illuminated. If the flight crews took no action at this point, the ownship would continue to encroach on the paired aircraft and would then receive another alert displayed as “MIN DISTANCE” on EICAS along with associated color changes and aural alerting. Flight crews were instructed during initial training that the proper course of action would be to notify ATC and terminate the FIM operation. A Traffic Alert and Collision Avoidance System (TCAS II) system was also resident to provide an additional layer of alerting and safety to supplement the FIM on-board alerts.

Results

Quantitative Measures

All quantitative results were analyzed with Analysis of Variance (ANOVA) with *a priori* significance level (α) of 0.05. Multivariate ANOVA (MANOVA) statistics were conducted for analyses with correlated dependent measures. No significant differences were found between Captain and First Officer and data was collapsed across the independent variable, $p > 0.05$.

Landing Performance. No statistical differences were found between the two interval management conditions, $p > 0.05$. This result was expected because the conditions were virtually the same once passing the FAF, where the flight crew disconnected the autopilot and completed the approach and landing flying manually using the EFVS. Because the current paper is focused on the FIM-S and FIM-DS comparison and off-nominal trial results, detailed description of landing performance is not provided here. However, the landing performance was almost, without exception, in the desired landing performance area, as defined by flight technical standards, for both the FIM-S and FIM-DS conditions. The data demonstrated that current efforts to extend EFVS operations beyond its current limits has merit and research should continue to determine the permissible operational credit allowable by these augmented vision technologies.

Interval Management Performance. No significant differences were found between the FIM-S and FIM-DS conditions for the dependent measures collected, $p > 0.05$. Inter-arrival statistics, between ownship and paired aircraft at the runway threshold, evinced an equal level of performance between the conditions. Overall, the actual spacing interval was 2.10 seconds (456 ft.) and 1.56 seconds (339 ft.) different from the assigned interval for FIM-S (assigned for 150 sec) and FIM-DS (assigned for 90 sec), respectively. Eighty-five percent arrived within 1 SD (1.20 sec) of the inter-arrival statistical mean and fully 100% of all cases were within 3 SD of the means under each interval management condition. The results correspond favorably to past FIM-S research which demonstrated that the majority of FIM-S aircraft has an inter-arrival interval within 2.5 sec from the assigned value and that 95% of aircraft are within 7.5 sec.

The data also showed that there were no significant differences in number of speed changes, executed throughout the arrival, between FIM-S (mean=5.5) and FIM-DS (mean=6.5). The FIM algorithm trended toward more commanded speed changes as the spacing was reduced for FIM-DS, but overall, this result was similar to that reported in other FIM-S research (e.g., [4], [12], [23]). The pilot comments did not indicate that the increased number of speed changes was obvious or objectionable.

Table 1 presents the inter-arrival time statistics for FIM-S and FIM-DS.

Table 1. Inter-Arrival Time Statistics

FIM-S	MEAN	152.10
	SD	1.15
	MAX	153.05
	MIN	147.45
FIM-DS	MEAN	91.56
	SD	1.20
	MAX	93.14
	MIN	87.58

Off-Nominal - Performance. In the off-nominal trials, all flight crews detected the conflict and performed either a go-around or contacted ATC to terminate operations. There were no overall significant differences in distance in-trail when this intervention occurred. The distance between paired aircraft and ownship was statistically non-significant FIM-S (mean=3.85 nmi) and FIM-DS (mean=3.10 nmi).

The “no-closer-than” restriction was 4 nmi and 3 nmi for FIM-S and FIM-DS, respectively. One-third of FIM-S participants went inside the no-closer-than range of 4 nmi prior to responding to the conflict. At the de-brief, these pilots remarked that they were anticipating the controller (i.e., researcher was pseudo-controller) would issue them vectors or speed changes as the aircraft approached the conflict aircraft since, under the FIM-S operation, the ANSP had responsibility for separation. Upon receiving a MIN DISTANCE alert triggered at the NCT distance, the flight crews immediately responded, highlighting the importance of an alerting and conformance monitoring system to be included in any FIM application. In no case was the distance so close that a TCAS alert was issued. Although several FIM-S flight crews did get within the NCT range of the paired aircraft, during the off-nominal trial, the

crews did not considered it to be a safety issue (closest or worse case was 2.95 nmi for FIM-S or 1.05 nmi closer than NCT specified; for FIM-DS, it was 2.80 nmi or 0.2 nmi closer than NCT specified).

Qualitative Measures

Post-run subjective data were collected to assess each pilot’s workload, situation awareness, and perception of system performance, operations, and safety. Pilot workload was measured with the Air Force Flight Technical Center Workload Estimation Scale. The scale provides a 7-point uni-dimensional scaled measurement of workload and has validated psychometric properties [24]. Situation Awareness was assessed through the ten-dimensional Situation Awareness Rating Technique (SART; [25]). Additional measures of situation awareness as well as the pilot’s perception of system performance, operations, and safety were gauged by questionnaires designed to allow for collection of interval measurement of the latent variable, based on [26].

Post-run questionnaire items were:

- Q1. Overall situation awareness of all traffic
- Q2. Situation awareness for spacing from paired traffic
- Q3. Efficacy of maintaining spacing from paired traffic
- Q4. Situation awareness for separation from paired traffic
- Q5. If applicable, efficacy of maintaining separation from paired traffic
- Q6. Overall perceived safety during approach using concept for traffic spacing
- Q7. If applicable, overall perceived safety during approach using concept for traffic separation
- Q8. Assessment of using EFVS for landing under visibility conditions tested during trial
- Q9. Perceived safety using EFVS for landing under visibility conditions tested during trial

In the qualitative measures analysis, no significant differences were found between Captain and First Officer and data was collapsed across the independent variable, $p > 0.05$.

Pilot Mental Workload. An ANOVA revealed a significant difference in workload ratings

between FIM-S and FIM-DS, $F(1, 71) = 152.71$, $p < 0.0001$. Flight crews reported the FIM-S (mean=4.21) to be significantly higher in mental workload than the FIM-DS (mean=3.03). A rating of “4” represents, “busy; challenging but manageable; adequate time available” compared to rating of “3” which was defined as, “moderate activity; easily managed; considerable spare time.”

Pilot Situation Awareness. The SART scale requires participants to rate 10 constructs on a 7-point scale; these ratings are summed to provide measures for three main constructs: Attentional Demands, Attentional Supply, and Understanding. These three ratings are then inserted into the equation to provide a single situation awareness (SA) value: $SA = \text{Understanding} - (\text{Demands} - \text{Supply})$. There was a significant difference for SART ratings, $F(1,71) = 5.34$, $p < 0.05$. Flight crews reported significantly higher situation awareness ratings for the FIM-DS condition (mean=6.45) compared to the FIM-S (mean=5.56). However, the difference is likely not practically significant; both conditions were rated as high for situation awareness.

The post-run questionnaire results for situation awareness support the SART findings. Seven-point Likert scales were used for the post-run questions with adjective anchors of “excellent” at a value of 1 and “poor” at a value of 5 on the scale. The pilots rated the overall traffic situation awareness (Q1) as nearly “excellent” for both the FIM-S (mean=1.85) and FIM-DS (mean=1.05). The differences were not statistically significant, $p > 0.10$. A marginally significant result was found for awareness of spacing from paired aircraft (Q2), $F(1,71) = 3.35$, $p < 0.10$. In the FIM-DS condition (question was not relevant for the FIM-S trials), flight crews rated, “situation awareness for separation from paired aircraft” to be “excellent” (mean=1.45) on average.

Table 2 presents the qualitative results for the post-run questionnaires.

Off-Nominal - Qualitative. For the off-nominal trials, pilot ratings for the FIM-DS (3.85) condition was marginally significant for workload

scale measure and was rated higher than the FIM-S (4.85), $F(1,11) = 4.05$, $p < 0.10$.

For situation awareness, there was a significant difference between FIM-S and FIM-DS post-test ratings for, “situation awareness for detection of traffic conflict”, $F(1,11) = 22.857$, $p < 0.001$. Pilots rated their awareness of the traffic conflict in the FIM-DS condition (mean=1.50) to be significantly better than the FIM-S (mean=2.83) condition. Similarly, the FIM-DS (mean=1.85) was rated higher for, “perceived amount of time available to detect and resolve traffic conflict with paired aircraft” compared to FIM-S (mean=3.0), $F(1,11) = 18.543$, $p < 0.001$.

No other significant differences were found for the post-run questionnaire applicable to comparison of FIM-S and FIM-DS operational concepts, $p > .05$.

Safety and Acceptability. Flight crews were asked to rate perceived safety and efficacy of FIM conditions (Q7). Overall, no significant differences were found between the two conditions for overall perceived safety, efficacy, or acceptability of concepts for conducting FIM operations, $p > 0.05$. No differences were reported between the FIM conditions for the off-nominal trials. There were also no significant differences found between FIM-S and FIM-DS for the pilot’s assessment of EFVS efficacy and safety for landing under visibility conditions tested, $p > 0.05$.

Discussion

NextGen represents a radically different approach to air traffic management requiring a dramatic shift in the tasks, roles, and responsibilities for the flight deck. One emerging NextGen concept - Equivalent Visual Operations (EVO) - can be achieved using an electronic means to provide sufficient visibility of the external world and other required flight references on flight deck displays that enable the safety, operational tempos, and visual flight rules (VFR)-like procedures for all weather conditions.

Table 2. Descriptive Statistics for Qualitative Measures for Nominal Trials

	IM-S				IM-DS			
	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX
Workload*	4.21	0.55	6	2	3.03	1.27	4	1
SART	5.56	1.23	4	8	6.45	1.65	5	9
Post-Run Questionnaire								
Q1	1.85	0.5	3	1	1.05	1.15	3	1
Q2	2.15	0.25	3	1	1.5	0.5	3	1
Q3	1.9	0.25	3	1	1.5	0.5	3	1
Q4	n/a	n/a	n/a	n/a	1.45	0.75	2	1
Q5	2.2	1.15	3	1	1.25	0.75	3	1
Q6	2.5	0.5	3	1	1.5	0.5	2	1
Q7	n/a	n/a	n/a	n/a	1.5	0.5	2	1
Q8	2	0.25	3	1	1.5	0.25	2	1
Q9	1.5	0.65	2	1	1.5	0.5	2	1
* lower score better								

This experiment evaluated the flight deck aspects of technologies for novel operational concepts, created by integrating the technologies of FIM and S/EVS - to support NextGen. The present research was focused specifically on a comparison of FIM-S and FIM-DS and the benefits derived by integration with S/EVS “vision-based” technology in support of the envisioned NextGen.

The results confirmed previous research [4] demonstrating the spacing precision enabled by FIM. In both the FIM-S and FIM-DS conditions, the mean spacing error at the threshold was less than 2 seconds, standard deviation less than 1.2 seconds, and the worst (maximum) spacing error in all cases was only 3.05 sec. These data suggest that FIM can significantly enhance the precision with which runway throughput can be controlled.

A key enabler to improve NextGen runway throughput has been postulated by FIM-DS where the pilot (flight crew) accept delegated responsibility for separation from the FIM-paired aircraft. The experiment evaluated FIM-DS where the flight crew manages their separation responsibility from the paired aircraft using appropriate displays of the FIM-S operation coupled with “vision-based” S/EVS technology. This concept flows from current FAA regulatory guidance where an approved EFVS may

be used in lieu of natural vision. The experiment results clearly demonstrated the efficacy of this concept. The FIM algorithm, as noted above, created precision spacing control and in the case of FIM-DS, a *60 second reduction* in the spacing was demonstrated. This spacing interval performance was considerably larger than the 20 to 30 second buffer currently added for aircraft arrival scheduling [27] and controller field data [28]. The data shows that the pilot workload and situation awareness (based on post-run SART data) was *improved* in the case of FIM-DS compared to FIM-S. During post-briefings, pilots reported that they were “a little more in-the-loop” with the FIM-DS condition because of the closer proximity to the paired aircraft and the delegated separation responsibility. When pilots accepted the separation responsibility, they became more involved – “tighter in the loop” – and thus, had better comprehension of the FIM operation, the surrounding traffic environment, and the aircraft state and trajectory.

This improvement for FIM-DS was most evident in the off-nominal trial where the paired aircraft failed to meet its planned threshold crossing time and created a loss of separation scenario. In both the FIM-S and FIM-DS cases, the crews identified the pending loss-of-separation and

requested ATC intervention, on average, with 3.1 nmi or 3.85 nmi separations for the FIM-DS and FIM-S cases, respectively. After the runs, the pilots in the FIM-DS reported significantly better awareness of the traffic situation than in the FIM-S. By accepting responsibility for separation, the pilots in the FIM-DS case were tighter in the loop, and more quickly reacted to the off-nominal situation. In the FIM-S case, the flight crews were sometimes passive and waiting for the ANSP to intervene even though they were aware of the loss-of-spacing. One-third of the flight crews only noticed after an EICAS message for “NCT” violation chimed.

While statistically significant differences in workload and situation awareness between FIM-S and FIM-DS were reported, the workload and SA were in all cases good to excellent. However, the performance and subjective ratings should be viewed in light of the design of the experiment and the flight deck equipage. First, the simulated NextGen environment was busy, but all traffic was equipped with ADS-B. A mixed equipage or failed/inoperative equipment situation was not simulated. Second, a state-of-the-art flight deck was used. As such, the FIM information formats were optimized. The FIM operation was monitored using the forward displays (ND and PFD) with appropriate alpha-numeric and map formats. Lastly (and possibly most importantly), the runway inset display concept on the ND created a tremendous increase in traffic awareness and preparedness within the operational context. By giving the crews an overview of the landing runway and the surrounding traffic, the crews were on top of the landing situation and were prepared to intervene if necessary and appropriate as the paired aircraft (and other traffic) landed and rolled out. This information is critical as the spacing distance significantly decreases on final approach. Runway occupancy is a critical issue today and will be an even more critical issue in NextGen to improve runway efficiency and throughput without degrading safety.

The simulated flight deck also included state-of-the-science S/EVS technologies as part of the “NextGen” baseline. FIM-DS was specifically enabled by the use of S/EVS (specifically, an EFVS) which is used in lieu of the pilot’s natural vision. In all cases, the landing performance for the EFVS manual approaches was shown to be similar in flight technical error to the visual condition landings and

auto-land performance, but these statistical comparisons are considered elsewhere (see, [29]). The limited data shown here demonstrated the efficacy of such systems to perform manual landings in visibilities as low as 700 ft RVR without the requirement of a certified auto-land system. Pilot comments and workload and SA ratings support that the pilots supported these concepts.

Pilots reported that the enhanced vision system provides “...an unparalleled level of safety”, “...was outstanding for seeing the runway and lights”, “...presented no issues in conducting the approach”, “...was easy to make the landing and would definitely use in these visibility conditions”, and “...much better than making Cat. IIIB landings without [EFVS] because you can actually ‘see’ where you are landing and not just looking at instruments.”

A critical issue for future research is to quantify the S/EVS performance standards sufficient to create “equivalent visual capability” in these operations. The FIM-DS was enabled in this experiment by a simulated FLIR. With regards to what improvements they desired of the FIM concepts, pilots commented that the aircraft target locator box on the HUD was too large and that it should be dynamically sized to provide range cues that are equivalent to what the eyes use to judge distances (i.e., monocular and inferred perceptual cues). Additional comments concerned the “fuzziness” and small size of the FLIR return for the paired aircraft due to the range from ownship. A need for feature extraction (machine vision) methods and contrast enhancement techniques was voiced to improve legibility of the paired aircraft in the EFVS.

It is also not clear that a real-time imaging sensor would be required or that other solutions may not avail themselves. For example, research has shown that operational concepts involving required-times-of-arrival may provide a similar level of performance with an upgrade to existing flight management systems (e.g., [30] – [31]). Surveillance by ATC or acceptance of separation responsibility by the flight crew in these conditions must be studied. Failure mode and loss-of-separation, such as that tested herein using non-normal and rare event scenarios must be conducted to tease out safety aspects of these concepts.

The simulated FLIR in this test was created from a physics-based model, but the weather

conditions of the test were tailored so they did not significantly degrade the FLIR performance. The limitation is that, like all enhanced vision sensors, visibility conditions can affect the ability of the system to “see” through the weather. That said, the advantage of the approach was the relative spacing capability, allowing flight crews to respond quickly to changes in the paired aircraft trajectory through the use of the enhanced vision system. This technology then dovetails seamlessly into an all-weather approach and landing. It helped to bridge the divide between the interval management concepts, from top-of-descent to final approach fix, and augmented vision system approach, landing, roll-out, and taxi. Together, they provide a potential comprehensive solution for all weather operations.

The required visibility (field-of-regard, range) and operating limitations, if applicable, must be considered. The pilots commented that the paired-aircraft traffic symbology on the HUD (and repeater) assisted measurably in the equivalent-visual separation task, but the traffic symbology should be range-based (i.e., the symbol size should be changed based on target range) and the FLIR image of the paired aircraft was blurred. While useable, a higher resolution and distinct image of the paired aircraft was desired.

Conclusions

The data supports the premise that FIM can improve runway throughput by more precisely spacing aircraft and that S/EVS, coupled with FIM, may provide reduced aircraft separation. Pilot workload, situation awareness and the perceived safety and acceptability of FIM-DS was equal, if not better, than FIM-S. This result was most evident during a staged off-nominal trial where, unbeknownst to the pilots, the paired aircraft unintentionally slowed down and created a potential loss-of-separation. A key component to these findings was the advanced flight deck display concepts supporting the FIM and S/EVS operation. This work vividly highlighted the synergistic integration of FIM and S/EVS technologies.

Future research should continue to refine flight-deck interval management and vision systems needed to support delegated separation and evaluate other operations that may benefit from the technologies, such as simultaneous dependent

parallel runway [32] and interval managed departures. Additional off-nominal scenarios need to be tested to ensure the safety/robustness of the operation. Variations in flight deck technologies should be evaluated to identify minimum performance standards. Finally, standards for what constitutes “equivalent vision” for these operations should be defined, including sensor and display performance for weather penetration/operability, field-of-view, resolution, latency, integrity, and availability.

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